

NONVOLATILE SOLID-STATE MAGNETIC MEMORY, METHOD  
FOR CONTROLLING COERCIVE FORCE OF NONVOLATILE  
SOLID-STATE MAGNETIC MEMORY, AND METHOD FOR  
RECORDING IN NONVOLATILE SOLID-STATE MAGNETIC MEMORY

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] This invention relates to a nonvolatile solid-state magnetic memory, a method for controlling the coercive force of a nonvolatile solid-state magnetic  
5 memory, and a method for recording in a nonvolatile solid-state magnetic memory.

Description of the prior art

[0002] With a nonvolatile solid-state magnetic memory having a ferro-  
magnetic layer as a recording layer, it is required for recording to apply a given  
10 external magnetic field to the recording layer. On the other hand, it is desired to develop the integration density of the nonvolatile solid-state magnetic memory, and in this point of view, the miniaturization for constituents of the nonvolatile solid-state magnetic memory such as the recording layer is desired.

[0003] The miniaturization causes the enhancement of the demagnetizing  
15 field in the recording layer, so that conventionally, it is required for recording in the nonvolatile solid-state magnetic memory to apply to the memory an external magnetic field large enough to invert the magnetization of the recording layer against the large demagnetizing field thereof. As a result, in recording, a large electric power consumption is required, and thus, the nonvolatile solid-state  
20 magnetic memory practically usable and of low electric power consumption was able to be provided.

[0004]

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a nonvolatile solid-  
25 state magnetic memory practically usable and of low electric power consumption.

[0005] For achieving the above object, this invention relates to a nonvolatile solid-state magnetic memory including a recording layer made of carrier induced ferromagnetic material.

[0006] This invention also relates to a method for controlling the coercive

force of a nonvolatile solid-state magnetic memory with a recording layer made of carrier induced ferromagnetic material, comprising the step of applying a given electric field to the recording layer so that the hole carrier concentration of the recording layer is reduced during recording.

5   **[0007]**     Moreover, this invention relates to a method for recording in a nonvolatile solid-state magnetic memory with a recording layer made of carrier induced ferromagnetic material, comprising the steps of:

          placing said nonvolatile solid-state magnetic memory under an external magnetic field to apply a given magnetic field of inversion to the recording layer,

10           and

          applying a given electric field to the recording layer under the magnetic field of inversion so that the hole carrier concentration of the recording layer can be reduced, to invert the magnetization of the recording layer and thus, perform recording operation for the nonvolatile solid-state magnetic memory.

15   **[0008]**     The carrier induced ferromagnetic material is one of new ferromagnetic semiconductors, and can control the magnetic property thereof by adjusting the carrier number and the carrier spin polarization by means of light or electric field. The inventors have conceived to utilize the carrier induced ferromagnetic material as a recording layer of a nonvolatile solid-state magnetic  
20   memory. In this case, by applying to the recording layer a given electric field so as to reduce the hole carrier concentration thereof, the coercive force of the recording layer can be controlled, and by adjusting the intensity of the electric field, the coercive force of the recording layer can be reduced. Therefore, the magnetization of the recording layer can be inverted with smaller external  
25   magnetic field and thus, recording performance for the nonvolatile solid-state magnetic memory can be done.

**[0009]**     As a result, according to the present invention, the nonvolatile solid-state magnetic memory practically usable and of low electric power consumption can be provided.

30   **[0010]**     In a preferred embodiment of the present invention, the nonvolatile solid-state magnetic memory is so constructed as to control the carrier concentration of the recording layer easily. Concretely, the recording layer is formed above a substrate, and a metallic electrode layer is formed above the recording

layer via an insulating layer, thereby to complete an electric field effect transistor. In this case, the recording layer functions as a channel layer, and the metallic electrode layer functions as a gate electrode. Therefore, the electric field for the reduction of the coercive force of the recording layer can be applied to the nonvolatile solid-state magnetic memory via the metallic electrode layer, and then, the recording operation for the nonvolatile solid-state magnetic memory can be simplified.

[0011] Other advantages and details of the present invention will be described below.

## BRIEF DESCRIPTION OF THE DRAWINGS

For better understanding of the present invention, reference is made to the attached drawings, wherein

Fig. 1 is a structural view showing a nonvolatile solid-state magnetic memory according to the present invention, and

Fig. 2 is a graph showing the relation between the electric field and the coercive force of the nonvolatile solid-state magnetic memory.

[0012]

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 is a structural view showing a nonvolatile solid-state magnetic memory according to the present invention. In the nonvolatile solid-state magnetic memory illustrated in Fig. 1, on a given substrate 1 are formed successively a buffer layer 2, a recording layer made of carrier induced ferromagnetic material, and a metallic electrode layer 5 via an insulating layer 4, thereby to complete an electric field effect transistor.

[0013] It is desired that the carrier induced ferromagnetic material forming the recording layer is ferromagnetic semiconductor such as (Ga, Mn)As or (In, Mn)As, which has excellent ferromagnetic semiconductor properties and whereby the recording operation for the nonvolatile solid-state magnetic memory according to the present invention can be performed in good condition and the recording information can be retained stably for a long time.

[0014] The thickness of the recording layer 3 is preferably set within 0.3-200nm, particularly within 3-10nm. In this case, the nonvolatile solid-state magnetic memory can be sufficiently miniaturized under the recording

performance in good condition and the stable retention of the recording information.

[0015] In the case that the recording layer 3 is made of the carrier induced ferromagnetic semiconductor as mentioned above, the substrate 1 is preferably made of GaAs single crystal. In this case, the recording layer 3 can be epitaxially grown in good crystallinity, to enhance the performance of the nonvolatile solid-state magnetic memory 10.

[0016] In Fig. 1, the buffer layer 3 is constructed of a multilayered structure composed of semiconductor layers 2A-2C. In this case, the difference in lattice constant between the substrate 1 and the recording layer 3 can be compensated effectively, to enhance the epitaxial growth of the recording layer 3 and thus, develop the performance of the nonvolatile solid-state magnetic memory 10 effectively and efficiently.

[0017] The multilayered buffer layer can be preferably employed when the recording layer 3 is made of (In, Mn)As and the substrate 1 is made of (001)GaAs single crystal. Since the mismatch in lattice constant between the (In, Mn)As and the (001)GaAs single crystal is about 7%, the use of the multilayered buffer layer can compensate the mismatch in lattice constant and thus, prompt the epitaxial growth of the recording layer 3. In this case, the semiconductor layer 2A is made of AlSb layer, and the semiconductor layer 2b is made of AlGaSb layer, and the semiconductor layer 2c is made of InAs layer.

[0018] The insulating layer 4 may be made of an inorganic material such as SiO<sub>2</sub>, SiN, Al<sub>2</sub>O<sub>3</sub> or an organic material such as polyimide. The metallic electrode layer 5 may be made of conductive metallic material such as Al or Au.

[0019] Then, a recording method using the nonvolatile solid-state magnetic memory 10 will be described below. Since the nonvolatile solid-state magnetic memory 10 is so constructed as the electric field effect transistor, the metallic electrode layer 5 functions as a gate electrode and the recording layer 3 functions as a channel layer.

[0020] First of all, the nonvolatile solid-state magnetic memory 10 is placed under an external magnetic field so as to apply to the recording layer 3 a given magnetic field of inversion. Then, a given electric field is applied to the recording layer 3 via the metallic electrode layer 5 so as to reduce the hole

concentration thereof. In this case, the coercive force of the recording layer 3 can be reduced, and if below the magnetic field of inversion, the magnetization of the recording layer 3 can be inverted and the recording for the recording layer 3 can be performed.

5 [0021] The intensity of the electric field to apply to the recording layer 3 is not restricted only if the recording performance is done, but preferably set within 0.01-10MV/cm, more preferably within 0.01-1mV/cm. In this case, irrespective of the physical properties such as thickness and the like of the recording layer 3, the coercive force of the recording layer 3 can be reduced within a range of 0.1-  
10 10mT and thus, the recording operation can be performed with a relatively small external magnetic field.

[0022] Under the range of the intensity of the electric field, the intensity of the external magnetic field is set within 0.1-10mT for recording.

[0023]

15 (Example)

In this Example, a nonvolatile solid-state magnetic memory as shown in Fig. 1 was fabricated. A (001)GaAs single crystal substrate was employed, and heated to 550°C. Then, an AlAs layer and an  $\text{Al}_{0.82}\text{Ga}_{0.18}\text{Sb}$  layer were successively formed in thicknesses of 50nm and 300nm, respectively on the  
20 substrate by means of MBE. Then, the substrate was cooled down to 450°C, and an InAs layer was formed in a thickness of 5nm by means of MBE, to complete a buffer layer.

[0024] Then, the substrate was cooled down to 250°C, and an  $(\text{In}_{0.967}\text{Mn}_{0.033})\text{As}$  layer as a recording layer was formed in a thickness of 4nm by means of MBE.

25 Then, an  $\text{SiO}_2$  insulating layer was formed in a thickness of 0.9  $\mu\text{m}$  by means of spin coating, and a Cr(5nm)/Au(95nm) as a metallic electrode layer was formed by means of deposition, thereby to complete an intended nonvolatile solid-state magnetic memory.

[0025] Fig. 2 is a graph showing the relation between the electric field and  
30 the coercive force of the nonvolatile solid-state magnetic memory at a temperature of 32K when the electric field is applied to the recording layer via the metallic electrode layer. As is apparent from Fig. 2, as the electric field is increased and the hole carrier concentration is decreased, the coercive force is

decreased and becomes very small within the positive electric field range. Therefore, by applying a relatively small external magnetic field as an inversion magnetic field, the magnetization of the recording layer can be inverted and thus, the recording operation can be performed.

5    **[0026]**     For example, since the coercive force of the recording layer is decreased below 0.2mT at the application of the electric field with an intensity of -0.5MV/cm or over, the magnetization of the recording layer can be inverted and thus, the recording operation can be performed by applying to the recording layer the external magnetic field with an intensity of 0.2mT. Therefore, it was turned  
10 out that the electric power consumption can be reduced remarkably.

**[0027]**     Although the present invention was described in detail with reference to the above examples, this invention is not limited to the above disclosure and every kind of variation and modification may be made without departing from the scope of the present invention.

15    **[0028]**     In the above-mentioned embodiment, for example, the nonvolatile solid-state magnetic memory is so constructed as the electric field effect transistor so that the hole carrier concentration of the recording layer is controlled by applying a given electric field thereto. However, a given protective layer is provided, instead of the metallic electrode layer 5, so that the  
20 carrier concentration of the recording layer can be controlled by irradiating an exciting light beam thereto from the outside. Moreover, the hole carrier concentration of the recording layer 3 can be controlled through the pn junction between the p-type (In, Mn)As ferromagnetic semiconductor and another n-type semiconductor joined with the ferromagnetic semiconductor.

25    **[0029]**     As mentioned above, according to the present invention, a nonvolatile solid-state magnetic memory practically recorded by a relatively small external magnetic field due to the sufficiently reduced coercive force thereof can be provided.